Acoustic Clutter and Ocean Acoustic Waveguide Remote Sensing (OAWRS) in Continental Shelf Environments

Principal Investigator: Nicholas C. Makris, Chief Scientist of ONR Ocean Acoustic Clutter Program
Massachusetts Institute of Technology, Department of Ocean Engineering
77 Massachusetts Avenue, Room 5-222
Cambridge, Massachusetts 02139
phone: (617) 258-6104   fax: (617) 253-2350   email: makris@mit.edu

LONG-TERM GOALS

Acoustic clutter is the primary problem encountered by active sonar systems operating in Continental Shelf environments. Clutter is defined as any returns from the environment that stand prominently above the diffuse and temporally decaying reverberation background and so can be confused with or camouflage returns from an intended target such as an underwater vehicle. Many environmental factors may contribute to acoustic clutter and adversely affect the performance of tactical Navy sonar by introducing false alarms in the system. In order to develop adaptive algorithms or technology to mitigate acoustic clutter, it is critical to identify, understand, and be able to accurately model the leading order physical mechanisms which cause clutter in existing sonar systems. The long-term goal of this program is to determine and understand the physical mechanisms that cause acoustic clutter in continental shelf environments and to use this knowledge to develop predictive tools to enhance the detection, localization and classification of underwater targets.

OBJECTIVES

The primary objectives of this program in FY2007 were to:

(1) Analyze Gulf of Maine 2006, MAE 2003 and ARE 2001 data to identify the primary cause of *discrete and target-like* clutter observed in typical continental shelf environments such as the Gulf of Maine and New Jersey Strataform areas.

(2) Characterize the temporal and spatial properties of biological clutter as well as correlation to oceanographic or geophysical properties of the environment. This includes examination of clutter features over the full diurnal cycle, including both day and night observations.

(3) Determine the physical scattering mechanisms causing biological clutter and their variation with fish species, depth, size and population density.

(4) Assess the impact of bioclutter on the performance of low frequency sonar in a variety of continental shelf environments around the world.

(5) Estimate velocity fields and dynamic forces driving clutter using a temporal sequence of consecutive low frequency wide-area sonar images to help distinguish biological scatterers from intended targets.

Report Documentation Page		*Form Approved* *OMB No. 0704-0188*

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1. REPORT DATE **30 SEP 2008**	2. REPORT TYPE **Annual**	3. DATES COVERED **00-00-2008 to 00-00-2008**

4. TITLE AND SUBTITLE **Acoustic Clutter And Ocean Acoustic Waveguide Remote Sensing (OAWRS) In Continental Shelf Environments**	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Massachusetts Institute of Technology, Department of Ocean Engineering,77 Massachusetts Avenue, Room 5-222,Cambridge,MA,02139**	8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES
code 1 only

14. ABSTRACT

Acoustic clutter is the primary problem encountered by active sonar systems operating in Continental Shelf environments. Clutter is defined as any returns from the environment that stand prominently above the diffuse and temporally decaying reverberation background and so can be confused with or camouflage returns from an intended target such as an underwater vehicle. Many environmental factors may contribute to acoustic clutter and adversely affect the performance of tactical Navy sonar by introducing false alarms in the system. In order to develop adaptive algorithms or technology to mitigate acoustic clutter, it is critical to identify, understand, and be able to accurately model the leading order physical mechanisms which cause clutter in existing sonar systems. The long-term goal of this program is to determine and understand the physical mechanisms that cause acoustic clutter in continental shelf environments and to use this knowledge to develop predictive tools to enhance the detection, localization and classification of underwater targets.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**10**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

(6) Estimate instantaneous clutter velocity distributions in a single wide area sonar image through Doppler.

(7) Quantify the idiosyncrasies in spatial and temporal evolution of biological scatterers in the Gulf of Maine that lead to target-like clutter.

(8) Model range-dependent scattering from the seafloor to distinguish moving clutter from statistically stationary background reverberation by tracking temporal and spatial fluctuations in long range sonar images.

(9) Develop and use a new, rapid, rigorous and unified range-dependent reverberation and waveguide target scattering model based on the parabolic equation, a Fleet standard, to quantitatively determine the fundamental physical mechanisms responsible for clutter in active sonar operation in Continental Shelf environments and to provide predictive tools to mitigate or tactically exploit clutter.

(10) Apply a newly developed theory by the PI and his group to explain the experimentally observed fluctuations in clutter, reverberation and calibrated target returns in shallow water.

(11) Develop and apply a new analytic model for the mean, covariance and temporal coherence of the acoustic field after multiple forward scattering through 3D inhomogeneities, such as internal waves, fish, bubbles, in an ocean waveguide, to explain a variety of observed acoustic transmission phenomenon in the deep ocean and in continental shelf environments, including attenuation, dispersion, scintillation.

(12) Conduct a joint experiment with the Mexican Navy in the Pacific Ocean to quantify hurricane destructive power with ocean acoustic measurements.

(13) Test the hypothesis that inexpensive underwater acoustic measurements can be used to determine the wind speed and classify the destructive power of a hurricane with greater accuracy than standard satellite remote sensing techniques and with at least the same accuracy as hurricane hunting aircraft.

(14) Develop and apply a theory for the nonlinear scattering of sound in the presence of inhomogeneities and apply it to underwater detection of submerged objects and objects buried in sediment.

APPROACH

The approach is to combine the analysis of experimental data with full-field waveguide modeling of forward propagation, clutter, acoustic reverberation, and target scattering. Under the Acoustic Clutter Program the Acoustic Clutter Reconnaissance Experiment (ARE) 2001 was primarily aimed at establishing the presence and persistence of acoustic clutter off the New Jersey continental shelf. The Main Acoustics Experiment (MAE) 2003 was designed to be very controlled, so that the actual mechanisms for the clutter could be established. It also had precise calibration so that theories and models could be accurately tested and validated. Full-field 3-D stochastic waveguide propagation and

scattering models, simulations and statistical studies helped direct experimental design and support the analysis and interpretation of experimental results. To include forward scattering, the approach is to develop a theory for calculating the attenuation and dispersion of an acoustic wave propagated through a medium containing random inhomogeneities and combine it with experimental evidence from MAE 2003 and Gulf of Maine 2006. The Gulf of Maine 2006 experiment was used to more carefully study simultaneously local scattering characteristics using conventional fish finding sonar (CFFS) as well as long range returns from both small schools and large shoals that lead to clutter in Navy sonar systems. This was done by use of both long-range Navy sonars in the low to mid frequency range as well as local conventional fish finding sonar and trawl vessels over an extended period of 3 weeks during both daytime and night time to examine the full diurnal variations of clutter.

Using a combination of propagation models, scattering models and wide area images from low frequency sonar, we study the spatio-temporal evolution of biological clutter, such as fish, over several days to identify their behavioral characteristics and ultimately help in clutter distinction. A Monte-Carlo approach based on the parabolic equation is applied to model acoustic wave propagation in a fluctuating ocean waveguide. Scattering from fish is quantified by modeling the fish-swimbladder as an air-filled bubble. To assess the performance of low frequency sonar in identifying biological clutter, we use both the model for scattering from biological targets and experimental data collected during MAE 2003 and Gulf of Maine 2006 experiments and invert for their physiological characteristics.

To include the effect of bottom reverberation, an analytic model is developed in range-dependent ocean environments and bistatic source-receiver geometries. This model is derived based on the Rayleigh_Born approximation to Green's theorem. It takes into account the full three-dimensional (3D) scattering from volume or surface inhomogeneities. The model is implemented in terms of scattering from the spatially varying resolution footprint of the sonar, typically determined by beamforming and temporal matched filtering. It is calibrated with ocean bottom reverberation data acquired by instantaneous ocean acoustic waveguide remote sensing (OAWRS) during the 2003 Main Acoustic Experiment and geophysical surveys of the ONR Geoclutter Program.

In our hurricane work, the approach is to deploy underwater acoustics sensors in the location on earth most frequented by hurricanes, collect data for a period of roughly one year and correlate that data with local wind speed measurements. This will then be compared against data collected at another site, in the Mid Atlantic, and theoretical predictions published by the PI.

WORK COMPLETED/RESULTS

Bioclutter and Remote Sensing of Fish Populations: We have developed an underwater remote sensing technology for instantaneously detecting, locating and imaging fish populations over thousands of square kilometers in continental-shelf environments [13]. Our new approach surveys at an areal rate roughly one million times greater than that of conventional fish finding methods. It does so by utilizing the ocean as an acoustic waveguide for efficient long-range propagation. With the technique, which we call Ocean Acoustic Waveguide Remote Sensing (OAWRS), we can continuously monitor fish population dynamics, behavior and abundance with minute to minute updates, producing records *unaliased* in space and time (essentially wide-area movies) that are valuable in the study of ocean ecology, conservation of ocean life, and preservation of marine fisheries.

We applied OAWRS in Sept-Oct 2006 in conjunction with the National Marine Fisheries (NMF) Annual Herring Survey of Georges Bank and the Gulf of Maine in a multinational, multi-institutional

oceanographic experiment sponsored by ONR, NOPP and the Sloan Foundation [3]. We observed a startling new pattern of diurnal behavior, and many other discoveries about the migrations of spawning herring, their population, and the frequency dependence of scattering. We obtained direct trawl samples confirming fish species.

The Gulf of Maine 2006 experiment was a great success in demonstrating that discrete clutter events are consistently the major clutter problem in a region with significant bathymetric relief and variable oceanography. In this experiment, as in MAE 2003, we found that fish shoals were the primary sources of clutter in long-range sonar systems. On all days of our experiment, we observed bioclutter very clearly emerge in our sonar imagery. We found diurnal patterns of variation in these bioclutter returns and quantified temporal scales within which they became extremely target-like.

To assess the performance of OAWRS in identifying biological clutter, we model the scattering from biological targets and invert for their physiological characteristics from experimental data collected during the Gulf of Maine 2006, as well as the earlier MAE 2003 experiment. This technique was successfully employed to identify Atlantic herring as the major constituent of the bioclutter observed in low frequency sonar imagery from the MAE 2003 experiment [2]. Scattering responses from biological targets vary significantly across different species of fish through dependent parameters such as fish length, depth and swimbladder volume. Fish swimbladder volume depends on neutral buoyancy depth, or the depth at which the weight of the fish is balanced by its buoyancy force. By constraining fish length and depth distributions from in-situ measurements, fish scattering response can be modeled as a function of a single parameter, the neutral buoyancy depth, which is closely linked to physiological behavior. Variations in neutral buoyancy depth lead to dramatic changes in scattering response at and below resonance. With measured scattering responses at these frequencies we can determine neutral buoyancy depth, which in turn reveals physiological characteristics that may provide supporting evidence for species classification. In our analysis of the MAE 2003 data, the expected average scattering response of a shoaling fish with constraints on the fish length and depth distribution was compared with the corresponding target strength for three frequencies 415 HZ, 925 Hz, and 1325 Hz. The best fit of low frequency target strength measurement to modeled scattering responses was given by a fish species that had a neutral buoyancy depth of 78 m with a resonance peak occurring at roughly 700 Hz. Combining this result with historical fish species distribution data in the region as well as established schooling behavior and fish biology attributes, we were able to identify the fish species.

Experimental data in the frequency range from 300 Hz to 1.2 kHz was also used to estimate mean low frequency target strength (TS) of spawning Atlantic herring populations in the Gulf of Maine [3]. These TS estimates exhibit significant variation over this frequency range (300 Hz to 1.2 kHz), in accordance with a physics-based resonant scattering model for swimbladder-bearing fish. The neutral buoyancy depth of herring and the species composition in the population is inferred by comparing the mean TS estimates with those derived from the model. Our analysis indicates the spawning herring population have a neutral buoyancy depth of between 80 to 100 m. We also find that the TS for herring found in water depths of 120-180m is much higher than expected because of these deep neutral buoyancy depths. This would then present serious problems for long range low frequency sonar when imaging intended targets, as they could get masked in returns from herring schools. Our analysis at different frequencies indicates that we can use the frequency characteristics of long-range clutter returns to help classify the bioclutter and distinguish it from intended targets.

We have demonstrated that fish schools are dominant cause of acoustic clutter in typical continental shelf environment using data from Acoustic Clutter Experiment 2001, 2003 and the Gulf of Maine

experiment of 2006. We showed in the Gulf of Maine as well as in the New Jersey Continental shelf that clutter features move with similar speed as underwater targets such as submarines and their spatial coherence scale is similar to many underwater targets, so that they can be easily confused with and misidentified as submarines. In order to study the dynamics of clutter in OAWRS imagery, we have developed and applied a new, innovative Acoustic Flow technique to determine flow fields, that requires little knowledge of the mechanisms underlying the scatterer dynamics [4]. The Acoustic Flow method enables us to determine velocity vectors from time varying density images formed using OAWRS in a continental shelf environment. The method has significant advantages over established techniques such as Optical Flow. First, it can deal with compressible motion which is a common characteristic of density images. Second, it does not require a knowledge of the underlying mechanisms that drive the motion field. The method has been applied to data from the MAE 2003 experiment. Quantitative measures of velocity fields explaining behavioral phenomena such as translation of fish groups are shown. Using the computed velocity fields we are now able to quantify the behavioral dynamics of biologically induced clutter such as fish groups over large spatial scales for the first time. We showed that typically, the magnitudes of the velocities are on the order of the typical fish velocities. We quantified specific behavioral phenomena like translation of fish groups, contraction and expansion of dense centers, as well as a depopulation episode involving flows through hourglass patterns. Quantifying this phenomena now helps us to predict the short time span behavior of these groups to help them in clutter classification.

Methods for modeling and estimating the mean and variance of the instantaneous velocities of clutter observed by OAWRS in an ocean waveguide have been developed. These are based on calculations of the Doppler shift and spread expected in long-range scattering from clutter in the continental shelf, which in turn are based on a general model for scattering from a moving target submerged in a stratified ocean waveguide [5]. The approach is used to classify clutter and distinguish it from intended targets.

Bottom reverberation and detection of submerged objects: An approach for distinguishing the scattered fields of moving targets from statistically stationary background reverberation in sonar data by tracking the temporal and spatial evolution of the returns has been developed [6]. An analytic model for 3D, bistatic scattering from medium inhomogeneities has been derived from first principles by application of Green's theorem. Statistical moments of the scattered field are expressed in terms of statistical moments of medium compressibility and density fluctuations. The model was applied to seabed reverberation and optimally calibrated with both OAWRS and geological data on the New Jersey continental shelf. Analysis with the model indicates that (1) seabed reverberation is incoherent, and (2) scattering strength varies with frequency depending on wavenumber k, medium coherence volume V_c and seabed depth penetration factor F_p following a $10\log_{10}(F_p V_c k^4)$ dependence. An efficient numerical approach is also developed for rapidly computing seabed reverberation over wide areas for bistatic sonar systems in range-dependent ocean waveguides. It exploits the correlation between monopole and dipole scattering terms and the limited penetration of acoustic fields in the seabed.

The high attenuation of acoustic field in ocean sediments is a problem for detecting buried objects, especially at high frequencies where attenuation increases. While attenuation may become negligible at low frequencies, these frequencies typically also lead to much lower target strengths and poorer resolution. We have developed a theory for nonlinear scattering of sound in the presence of an inhomogeneity insonified by two plane waves at slightly different frequency [7]. The use of two waves results in sum and difference frequency waves that, by appropriate choice of the incident frequencies, can achieve both higher penetration into sediment and better resolution. If we choose a pair of low

frequency incident waves, we can achieve high penetration into the sediment and at the same time achieve high resolution by utilizing the sum frequency wave. We have derived the governing equation for the second-order terms and have provided a solution by introducing three different mechanisms for the generation of the scattered wave. For objects with different geometries and acoustic properties we have shown that the contribution of each mechanism, and consequently the physics of the response are different. Exploiting these differences is key in detecting and discriminating submerged and buried objects.

Acoustic Propagation (Multiple Forward Scattering) Through a Fluctuating or Randomly Inhomogeneous Ocean: Sound waves in the ocean, like light in the atmosphere, twinkle as they pass through a turbulent or changing medium. We derived perhaps the only analytic solution available for acoustic field propagating through an ocean with random 3-D inhomogeneities[14] in terms of waveguide modes. Although the derivation was lengthy, the final expressions are extremely compact, intuitively appealing and generally applicable to any kind of inhomogeneity in the ocean. This model makes it possible to quickly and intuitively determine when an acoustic field will remain coherent, or deterministic, when and how it will fluctuate incoherently, and how much attenuation to expect from scattering. While scintillation is sometimes a problem for remote sensing, it can also be advantageous since it smooths over complicated interference patterns that characterize propagation through a deterministic ocean, making it actually easier to remotely image distant objects.

We have extended our analytical model to determine the temporal coherence of sound after propagation through a slowly time-varying random medium [8]. This model has been used to explain the roughly 10-minute time scale of acoustic field fluctuations observed at mega meter ranges in the North Pacific during Acoustic Thermometry of Ocean Climate (ATOC) experiments. It is shown that the time scale of acoustic field fluctuations is non-linearly related to the much longer 3-hour coherence time scale of deep ocean internal waves through a process of multiple forward scattering. We have also shown that 3D scattering effects become pronounced when the acoustic Fresnel width exceeds the cross-range coherence length of the deep ocean internal waves, which lead to frequency and range-dependent power losses in the forward field that may help to explain historic long range measurements.

Fish shoals may sometimes lead to measurable attenuation in the forward field and can affect the performance of low frequency sonar. Analytical expressions have been derived for the attenuation and dispersion of the acoustic field forward propagated through fish shoals and wind-generated bubble clouds in an ocean waveguide [9]. It is found that at swim bladder resonance, fish shoals may sometimes lead to measurable attenuations in the forward field. The attenuation at off-resonant OAWRS frequencies, however, is typically negligible as shown both by the present theory and experimental data. The modeled attenuation due to random wind-generated bubble clouds is found to be highly sensitive to the choice of cutoff radius, which determines whether resonant bubbles are included in the bubble spectra. It is also found that bubble clouds generated under high wind speeds lead to additional dispersion and attention of the transmitted signal. These expected distortions can significantly degrade standard coherent processing techniques in ocean acoustics, such as the match filter, if not taken into account.

Quantifying Hurricane Destructive Power with Undersea Sound: Passive ocean acoustic measurements may provide a safe and inexpensive means of accurately quantifying the destructive power of a hurricane. This is demonstrated by correlating the underwater sound intensity of hurricane Gert with meteorological data acquired by aircraft transects and satellite surveillance [10]. The

intensity of low frequency underwater sound measured directly below the hurricane is found to be approximately proportional to the cube of the local wind speed, or the wind power. We have shown that passive underwater acoustic intensity measurements may be used to estimate wind speed and quantify the destructive power of a hurricane with an accuracy similar to that of aircraft measurements. The empirical relationship between wind speed and noise intensity may also be used to quantify sea-salt and gas exchange rates between the ocean and atmosphere, and the impact of underwater ambient noise on marine life and sonar system performance.

To obtain more data relating undersea sound and wind power in hurricanes, Professor Makris initiated and is currently leading a joint scientific collaboration with Mexico's Navy (Secretaria De Marina). Professor Makris worked for several years with various ONR Latin America Station Chiefs and Program Managers and the US Embassy in Mexico City, to establish relationships with Mexico and obtain support from the Admiral commanding the Directorate of Oceanography, Hydrology and Meteorology. In June 2007, with generous collaboration from Mexico, which supplied one of its best oceanographic research vessels for two weeks, Prof. Makris led a scientific expedition with the Commander of Mexico's Instituto Oceanographico Pacifico, and officers from Secretaria De Marina, to Mexico's remote Pacific Isla Socorro, restricted to all but Navy personnel and special guests. Socorro experiences more hurricanes than anywhere else on earth. Two acoustic sensors were deployed within kilometers of shore near Secretaria De Marina's meteorological station. Besides hurricane data, we also expect to collect a novel and rich set of bio-acoustic data, since Isla Socorro is surrounded by a famous marine sanctuary inhabited by many vocalizing creatures such as humpback whales. We have successfully retrieved the sensor off Isla Socorro, and are currently analyzing the acoustic data collected over the deployed time period. During the period of deployment near Isla Socorro, no hurricane passed near the island, and so we were not able to correlate the recorded underwater noise intensity with high wind speeds that would be found in a hurricane. Another follow-up experiment in the same geographical location has been designed and two more sensors will be deployed in Spring 2009.

IMPACT/APPLICATIONS

- We have designed and conducted a major international oceanographic experiment to study acoustic clutter in the Gulf of Maine in the fall of 2006. We found that as in the New Jersey Strataform area, the primary cause of acoustic clutter is densely populated fish schools. We have measured the depth, frequency, spatial and temporal characteristics of this clutter to help mitigate it in Navy sonar systems.

- We have determined key physiological characteristics of Atlantic herring, such as neutral buoyancy depth, in the New Jersey continental shelf, using an analytical model for the fish TS and measurements of low frequency TS obtained in the MAE 2003 experiment. Our method now enables assessment of the impact of bioclutter on the performance of OAWRS in a variety of continental shelf environments around the world.

- We have determined the low frequency TS of Atlantic herring located between 120-180m water depth in the Georges Bank, and found it to be much higher than expected. This is because the neutral buoyancy depth is very deep, about 105 m, for these shoals. Quantifying the low frequency TS helps mitigate problems in low frequency sonar when imaging target-like clutter.

- We have developed a new technique that uses a temporal sequence of consecutive low frequency wide-area sonar images to estimate the flow fields of clutter from OAWRS images. This technique provides us spatio-temporal characteristics of clutter dynamics that are vital to distinguish biological scatterers from intended targets.

- We have developed an analytical tool to estimate instantaneous clutter velocity distributions in a single wide area sonar image through Doppler.

- We have developed a theory for nonlinear scattering of sound in the presence of an inhomogeneity insonified by two plane waves at slightly different frequency, and have explained the mechanisms through which sum and difference frequency waves are generated. Our theory can be used in detection and discrimination of objects buried in seafloor sediments, by simultaneously using the high penetration of the incident low frequency waves and the high resolution of the sum frequency wave.

- We have developed and applied a new analytic model for the mean, covariance and temporal coherence of the acoustic field after multiple forward scattering through 3D inhomogeneities, such as internal waves, fish, bubbles, in an ocean waveguide. We are now able to explain a variety of observed acoustic transmission phenomenon in the deep ocean and in continental shelf environments, including attenuation, dispersion, scintillation.

- We have developed an approach for distinguishing the scattered fields of moving targets from statistically stationary background reverberation in sonar data by tracking the temporal and spatial evolution of the returns.

- We have proposed and developed a method to estimate hurricane destructive power using underwater noise measurements obtained from relatively inexpensive underwater hydrophones. This method can be used in hurricane prone areas around the world, in place of prohibitively expensive specialized hurricane hunting aircrafts.

- We have developed a partnership with the Mexican Navy to conduct scientific experiments in their waters to study ocean acoustic hurricane quantification. We will deploy sensors off the Mexican Isla Socorro, which experiences more hurricanes than anywhere else on earth. When retrieved in 2010, these will be used to test the ability to accurately quantify hurricane destructive power with acoustics.

TRANSITIONS

Transition of the Acoustic Clutter Program is already significant as documented by the great amount of Naval Research now focusing on clutter issues in active sonar which was spearheaded and guided by this Acoustic Clutter Program. Our hurricane work can be transitioned into development of ocean based early warning systems off USA, Mexico and other coastal regions around the world frequented by hurricanes.

RELATED PROJECTS

Other organizations participating in the Geoclutter Program are Northeastern University, National Marine Fisheries Service, Institute of Marine Research Norway, NRL, ARL-PSU, MAI, UNH, RESON, SNWSC, and NFESC.

RECENT RELEVANT PUBLICATIONS

1. P. Ratilal, et. al., and N. C. Makris, "Hundreds of Millions of Herring Abruptly Conform to Synchronous Spawning Queues Across Georges Bank," submitted to Science.

2. S. Jagannathan, D. Symonds, I. Bertsatos, T. Chen, M. Andrews, Z. Gong, N. Donabed, H. T. Nia, A. Tan, L. Ngor, R. Nero, J.M. Jech, O.R. Godø, S. Lee, P. Ratilal and N.C. Makris, "Ocean Acoustic Waveguide Remote Sensing (OAWRS) of Marine Ecosystems," submitted to the Mar. Ecol. Prog. Ser.

3. Z. Gong, M. Andrews, D. Cocuzzo, S. Dasgupta, S. Jagannathan, D. Symonds, I. Bertsatos, T. Chen, H. Pena, R. Patel, O.R. Godø, R. W. Nero, J. M. Jech, N.C. Makris and P. Ratilal, "Atlantic Herring Low Frequency Target Strength and Abundance Estimation:OAWRS 2006 Experiment in the Gulf of Maine," submitted to Can. J. Fish. Aquat. Sci.

4. S. Jagannathan, B.K.P. Horn, P.Ratilal, N.C.Makris, "Velocity Estimation and Prediction from Time Varying Density Images," submitted to IEEE Trans. Pattern Analysis and Machine Intelligence.

5. I. Bertsatos and N.C. Makris, "Instantaneous Velocity estimation of Fish Groups by Ocean-Acoustic Waveguide Remote Sensing Doppler Analysis," to be submitted to J. Acoust. Soc. Am.

6. A. Galinde, N. Donabed, M. Andrews, S. Lee, N.C. Makris and P. Ratilal, "Range-dependent Waveguide Scattering Model Calibrated for Bottom Reverberation in Continental Shelf Environments" J. Acoust. Soc. Am 123, 1270-1281 (2008)

7. H.T.Nia, P.Ratilal, N.C. Makris, "Nonlinear Scattering of Sound in the Presence of Inhomogeneities at Dual Frequency," submitted to Phys. Rev. E.

8. T. Chen, P. Ratilal, N. C. Makris, "Temporal Coherence After Multiple Forward Scattering Through Random Three-dimensional Inhomogeneities in an Ocean Waveguide," J. Acoust. Soc. America (in press)

9. T. Chen, P. Ratilal, N. C. Makris, "Attenuation due to Fish Shoals and Wind-generated Bubble Clouds After Multiple Forward Scattering," submitted to J. Acoust. Soc. Am.

10. J.D.Wilson and N.C. Makris, "Quantifying hurricane destructive power, wind speed and air-sea material exchange with natural undersea sound," Geophys. Res. Lett. 35, L10603.

11. M. Andrews, T. Chen and P. Ratilal, "Broadband transmission statistics and match filter degradation in the New Jersey Continental shelf," under review in J. Acoust. Soc. Am. (2008).

12. I. Bertsatos, S. Lee and N.C. Makris, "Optimal Passive Source Localization in a Fluctuating Ocean Waveguide by Nonlinear Matched Field Inversion and by the Array Invariant Technique," to be submitted to J. Acoust. Soc. Am.

13. N.C. Makris, P.Ratilal, D. Symonds, S. Jagannathan, S. Lee and R.W. Nero, "Fish Population and Behavior Revealed by Instantaneous Continental Shelf-Scale Imaging," Science, 311, 660-663.

14. P. Ratilal and N.C. Makris, "Mean and covariance of the forward field propagated through a stratified ocean waveguide with three-dimensional random inhomogeneities," J. Acoust. Soc. Am. 118, 3560-3574 (2005)